VGOS Observations with Westford, GGAO, and the New Station at Kokee, Hawaii

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Abstract The GGAO 12-m and Westford 18-m antennas are instrumented with the four-band broadband signal chain to provide VGOS capability. These antennas have been making VGOS geodetic observations for more than a year. Preliminary analysis of the thirteen sessions, which range in duration from one to 15 hours, gives a weighted RMS deviation of 2 mm from the mean baseline length (601 km). The 12-m VGOS antenna at Kokee Park Geophysical Observatory on Kauai, HI, was completed in early 2016, and the broadband signal chain, built by MIT Haystack Observatory, was installed. Observations with the GGAO12M and Westford antennas began in February. These will increase in duration from one to 24 hours with completion of the Commissioning Phase for KOKEE12M expected in May 2016.

Keywords VGOS, broadband VLBI, geodesy

1 Introduction

The goal of the next-generation geodetic VLBI system is to achieve station position uncertainty of approximately 1 mm and velocity uncertainty of better than 0.1 mm/year. Studies by the IVS Working Group 3 [4] determined that the primary error source is expected to be unmodeled atmosphere delay variation and that this error is reduced by increasing the number of observations per hour. This implies faster antennas, but for economic reasons the resulting antenna collecting area for the same cost is significantly smaller, thus implying lower sensitivity for the same receiver systems. To recover the sensitivity a higher recording data rate was proposed, to be achieved by utilizing more RF bandwidth and by implementing dual polarization on the antennas. The delay uncertainty would be reduced, for the same antenna efficiency, by covering a wider frequency range than the 2 to 9 GHz of the existing geodetic VLBI network. The result of the WG3 studies was to propose the use of four 1-GHz bands spanning the radio frequency band from S-band (2.2 GHz) to 14 GHz.

This broadband design, originally called VLBI2010 but now referred to as VGOS (VLBI Global Observing System), was implemented on two prototype systems: a 12-m antenna at the Goddard Geophysical and Astronomical Observatory (GGAO) of the Goddard Space Flight Center near Washington, D.C., and the Westford 18-m antenna at Haystack Observatory near Boston, Massachusetts, USA, to prepare for the development and implementation of the first operational VGOS antenna at Kokee Park Geophysical Observatory (KPGO). The KPGO VGOS antenna, which began observations in February 2016, has been a cooperative project of the U.S. Naval Observatory, NASA, and MIT Haystack Observatory.

The GGAO and Westford antennas began geodetic VLBI observations in December 2014 with the VGOS Demonstration Series (VDS). Results from that set of sessions spanning 14 months are reported here, along with some preliminary results for the KPGO VGOS antenna. Additional information about the KPGO system is provided in the reports in this volume by Rajagopalan (2016) [5] and by Ruszczyk (2016) [6].

MIT Haystack Observatory

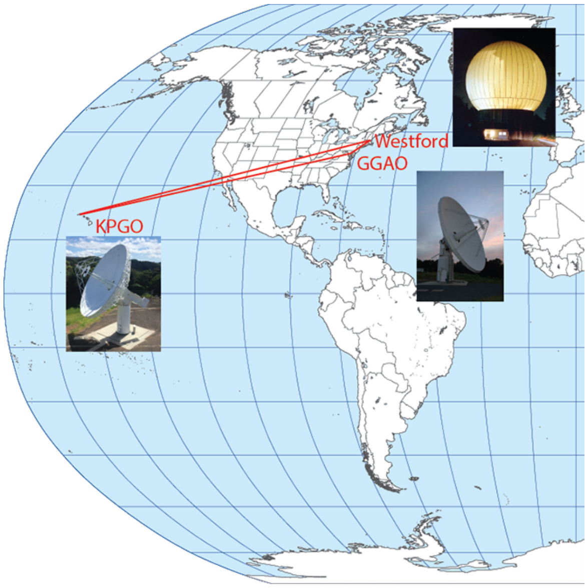

Fig. 1 The first operational VGOS antenna systems.

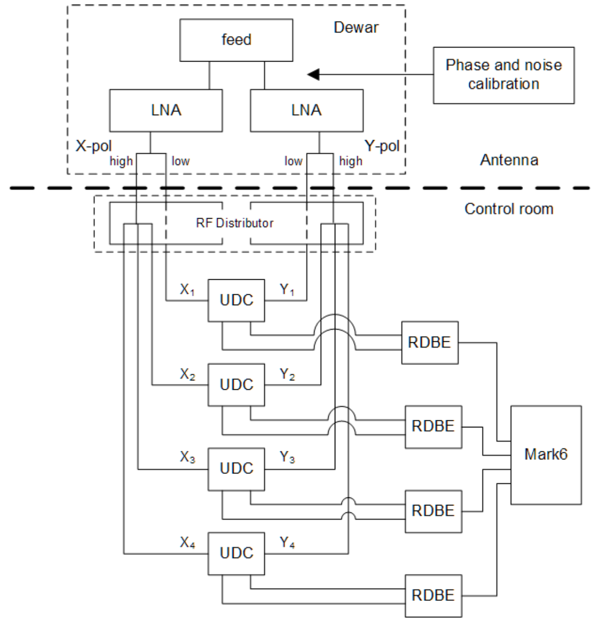

Fig. 2 Broadband signal chain configuration for GGAO 12-m, Westford, and Kokee 12-m antennas (Haystack implementation).

2 VGOS Broadband System Features

The features of the VGOS system as implemented on the GGAO12M and Westford antennas are repeated here for reference:

- four bands of 512 MHz each, rather than the two (S and X) for the legacy Mark IV systems,
- dual-linear polarization in all bands,
- multitone phasecal delay for every channel in both polarizations,
- group delay estimation from the full spanned bandwidth (3.0 GHz to 10.5 GHz),
- simultaneous estimation of the group delay and the total electron content difference (dTEC) between sites using the phases across all four bands.

A major difference between the broadband systems and the legacy S/X systems is the use of both linear polarizations rather than just one circular polarization.

The current configuration of the broadband signal chain for GGAO12M, Westford, and KOKEE12M is shown in Figure 2.

Two significant differences between the analysis of broadband data and that of standard S/X geodetic VLBI data are the required use of multitone phase cal delay to align the four bands and the simultaneous estimation of the group delay and the dispersive effect of the differential along-path charged particle content (the 'ionosphere'). An additional instrumental effect that required investigation and implementation is the difference, between polarizations, of the uncalibrated delays and phases that arise primarily in the feed and cables that precede injection of the phase calibration signal in the front end.

3 Observations, Correlation, and Analysis

In late 2014 a series of bi-weekly one-hour sessions, called the VGOS Demonstration Series (VDS), was initiated in order to bring the new observation technique to operational capability. The emphasis has been on completion of Field System control of all equipment, evaluation of the equipment for sustained operation, implementation of the additional correlation and post-correlation analysis tools needed for the broadband hardware capability, and development of the procedures for all of these steps to provide minimum personnel interaction at all stages. Each of these leads toward the goal of unattended operation.

An objective of the VGOS design is the ability to observe with the legacy systems at S and X bands. However, radio frequency interference (RFI) at S-band can severely degrade the sensitivity of the systems. For the results reported here, and perhaps for future VGOS-only sessions, the lower frequency bound was chosen to be 3 GHz. Also, while the goal for the upper frequency of the VGOS observations is 14 GHz, the GGAO and Westford systems, which are prototypes, are limited by the down-conversion hardware (UDC in Figure 2) to an upper bound of about 11 GHz. Taking into account the need to estimate the line-of-sight charged particle dispersion, the optimum band frequencies were calculated by Bill Petrachenko to be centered on approximately 3.3 GHz, 5.5 GHz, 6.6 GHz, and 10.5 GHz.

From December 2014 through February 2016 thirteen sessions were successful. Hardware problems plagued both antennas through the second half of 2015, but observations resumed in November.

The following list summarizes the various processes involved in the data collection and processing of the recent VGOS observing sessions:

- make a schedule,
- perform the observations,
- transfer the data to the correlator, either by shipping the disk modules or by network transfer,
- correlate simultaneously all four polarization products for all four bands directly from the Mark 6,
- estimate the group delay using *fourfit*
  - applying multitone phasecal delays and phases to align the phases of the four bands,
  - correcting for uncalibrated delay and phase offsets between polarizations,
  - combining the four polarization products (HH/VV/HV/VH) to produce a pseudo-Stokes I visibility [2] providing a single amplitude, group delay, and phase,
- create a database,
- estimate the geodetic and ancillary parameters with nuSolve [1].

More details on the observation, correlation, observable extraction (fringe fitting), and geodetic analysis are provided in [3]. Since that report a significant advance has been made towards the realization of the VGOS goal of improved analysis capability by incorporating the use of the new vgosDB and associated utilities [1] for all sessions in 2016.

4 Preliminary Results from VDS

The geodetic analysis was done for each session separately using the new program *nuSolve* from GSFC [1]. *nuSolve* provides all of the needed operations and modeling that is useful for inspection, evaluation, and parameterization of the VDS sessions.

For the *nuSolve* analysis, since these were mostly only one-hour sessions, the model parameterization was relatively simple. Only the clock behavior at GGAO, the position of GGAO, and the atmosphere zenith delays and gradients at both stations were estimated. The clocks and atmospheres were modeled as one-hour piecewise-linear (PWL) functions using the default constraints from *nuSolve*. While the median formal uncertainty for the group delay for the VDS sessions is less than three picoseconds (including accounting for the correlation of the group delay and charged particle dispersion (e.g., ionosphere)), the actual scatter is much larger, probably due primarily to unmodeled atmosphere fluctuations. To achieve a chi-square per degree of freedom of $\sim$1, an additional delay of 5–10 picoseconds was added quadratically to the formal uncertainty of each scan. The post-fit delay residuals for the longest VDS session are shown in Figure 3. Outliers greater than 3-sigma after re-weighting were excluded. The weighted RMS value is 6.8 ps.

The length of the baseline between the two antennas is approximately 601 km, oriented northeast-southwest. The residuals of the length estimates about the mean for the thirteen sessions are shown in Figure 4. The durations of the sessions are 1–1.5 hours

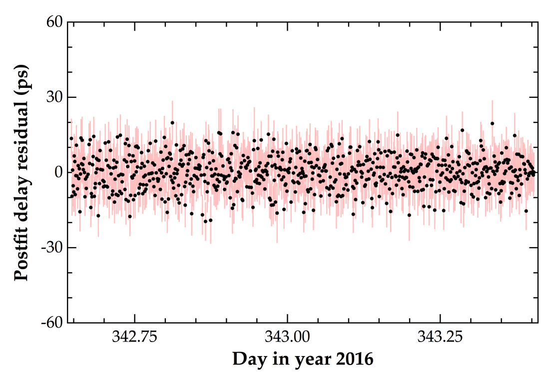

Fig. 3 Group delay post-fit residuals for V15342 after re-weighting.

for all but DOY 328 (five hours) and DOY 342 (15 hours). Possible reasons for the apparent inconsistency in length estimate are discussed in the next section.

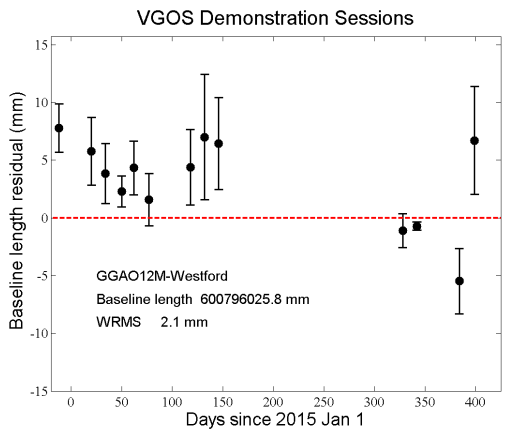

Fig. 4 Length residuals of the 13 VDS sessions.

5 Cable Delay Calibration

A shortcoming in the instrumentation at both sites is the lack of the new cable delay measurement system (CDMS, developed for KOKEE12M) for the cable carrying the 5-MHz reference signal from the maser to the phase calibration generator in the front end. Any variation of delay in this cable would produce an uncorrected variation in the observed delay. If this variation is correlated with antenna position, it may result in an error in the estimated position. The most common problem is for the delay to vary due to cable stretching with motion in elevation or in azimuth (or both). In order to assess the possible magnitude of this effect, the multitone phasecal delay was measured while moving each antenna in azimuth and elevation (not as part of a VLBI session), with the results given in the following section.

5.1 Westford

A Mark IV cable calibrator was installed at Westford in December 2015 but was not used consistently. However, measurements of the azimuth and elevation dependence of the multitone phase cal delay in a special observing session and measurements of the cable delay for the sessions, where present, indicate that any uncalibrated horizontal position error, and thus baseline length change, is probably less than two millimeters.

5.2 GGAO

In June 2015 (DOY 180) the peak-to-peak variation in multitone phase cal delay was less than 10 ps as the antenna was moved systematically in azimuth and elevation. By November (DOY 322) it was up to 60 ps and reached over 100 ps by the last session reported. The variation in multitone phase cal delay in all bands at GGAO, when corrected for, could possibly change the apparent position of GGAO by up to 10 mm. This degradation in cable stability is inferred to be due to changes in the coaxial cable carrying the 5-MHz reference signal to the phase cal generator, since the large variation decreased to almost zero when that cable was replaced.

A potential method of correcting for this effect is to use the multitone phase cal delay dependence on azimuth and elevation as a proxy for the cable delay measurement, but this has not been evaluated yet.

6 KOKEE12M

The KOKEE12m antenna, funded by the U.S. Naval Observatory, built by InterTronics Solutions, and implemented with the four-band broadband delay signal chain, is the first operational system meeting most VGOS specifications. While the optics are identical to the GGAO 12-m antenna, the Kokee antenna has improved az-el motion and achieves the slew rates of 12°/second in azimuth and 5°/second in elevation that is specified for VGOS-compatible systems. The signal chain, funded by NASA and implemented by MIT Haystack Observatory, evolved from the version that was constructed for the GGAO 12-m antenna but has some improvements, most notably the inclusion of the CDMS and a somewhat wider frequency coverage. Access to frequencies up to 14 GHz is attained through changes in the UpDown Converter and the use of later versions of the low-noise amplifiers and QRFH feed from Caltech.

KOKEE12M has made broadband observations in several sessions with GGAO12M and Westford. The post-fit delay residuals (without re-weighting) are shown in Figure 5 for one session. See the papers in this volume by Rajagopalan (2016) [5] and by Ruszczyk (2016) [6] for additional information about KOKEE12M.

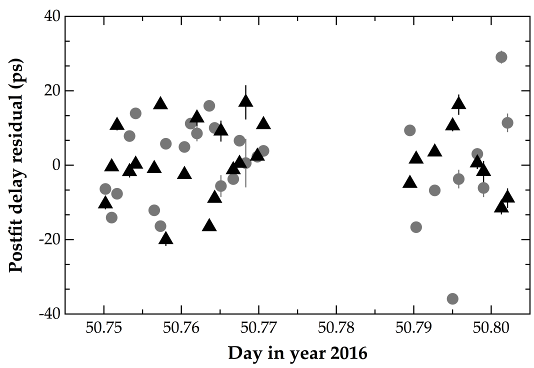

Fig. 5 Post-fit delay residuals for the KOKEE12M–GGAO12M (circles) and KOKEE12M–Westford (triangles) baselines with no re-weighting. The 1-sigma formal delay uncertainties, based solely on signal-to-noise ratio, are indicated by the error bars, most of which are smaller than the symbols. The median uncertainty is less than two picoseconds for each of the thirty-second scans.

7 Plans

Following completion of the KOKEE12M VGOS system, observing will switch to commissioning sessions to develop and demonstrate the capabilities and operations of the new antenna in conjunction with GGAO12M and Westford. A sequence of one-hour sessions, similar to the VDS, will initiate the series, and the duration will increase until several successful 24-hour sessions have been completed.

Acknowledgements

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